

# **Effects of Confining Pressure on the Crack Growth Behavior in a Filled Elastomer Subjected to a Constant Strain Rate**

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## **ABSTRACT**

In this study, the effects of different confining pressures and initial crack lengths on the crack growth behavior in a highly filled elastomer were investigated. The material under investigation contains hard particles embedded in a rubbery matrix. The specimens were strained at a constant strain rate of 16.67 in/in/min. Two confining pressures, 500 psi and 1000 psi, and two initial crack lengths, 0.1 in. and 0.3 in. were considered. The experimental data were analyzed and the results are discussed.

## **INTRODUCTION**

Particle reinforced composites are widely used for attaining increased modulus, strength and/or toughness depending on the application. Such composites exhibit a non-linear constitutive response due to various factors such as damage (debonding, cavity or vacuole formation, cracking), hysteresis during loading-unloading (Mullins effect), viscoelasticity (time dependence, material, damage, and environment) and large strains (geometric). The structural integrity, expected life, and their proper functioning are intimately related to the fracture behavior of these materials undergoing damage.

The fracture behavior of particulate composites such as rubber-toughened epoxies and solid propellants has been widely investigated experimentally [1-6]. Modeling efforts have been mostly related to correlate crack propagation to Mode I stress intensity factor based on the concept developed by Knauss and Schapery for viscoelastic fracture. There has been relatively little effort in understanding the effect of confining pressure and strain rate on the crack growth behavior in the particulate composites.

In this study, pre-cracked uniaxial specimens were used to study crack growth behavior in a highly filled elastomer, containing hard particle embedded in a rubbery matrix. The specimens were subjected to a constant strain rate, 16.67 in/in/min, at two different confining pressures, 500 psi and 1000 psi. Two initial crack lengths, 0.1 in. and 0.3 in., were considered. The experimental data were analyzed, and the effects of the confining pressure and the initial crack length on the crack growth behavior are discussed.

## **THE EXPERIMENTS**

In this study, specimens with an edge crack were used to investigate the crack growth behavior in a highly filled elastomer subjected to a constant strain rate of 16.67 in/in/min at 500 psi and 1000 psi confined pressures. The geometry of the pre-cracked specimen is shown in Fig.1. Prior to conducting the tests, the specimen was loaded in the testing machine inside a pressure chamber. When the pressure inside the pressure chamber reached the predetermined value, the specimen was

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straining at the constant strain rate until it broke. During the test, a high-speed camera was used to monitor the crack growth. In addition, the load and time were also recorded. These raw data were used to determine the stress, strain, Mode I stress intensity factor,  $K_I$ , crack length,  $a$ , and crack growth rate,  $da/dt$ .

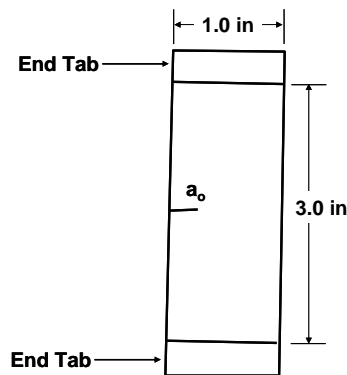


Fig.1 Specimen Geometry

The raw data obtained from the constant strain rate tests were the crack length,  $a$ , the time,  $t$ , and the load,  $p$ , corresponding to the measured crack length. The recorded experimental data,  $a$ ,  $t$ , and  $p$ , were used to calculate  $K_I$  and  $da/dt$ . In calculating  $K_I$  for a given set of values of  $a$  and  $p$ , a nonlinear regression equation, which relates the normalized stress intensity factor,  $K_I/p$ , to the crack length,  $a$ , was used. The values of  $K_I/p$  for different crack lengths were determined from the ABAQUS computer program. The crack growth rates,  $da/dt$ , as a function of time were calculated. In calculating  $da/dt$ , the secant method was used. In the secant method, the crack growth rate is computed by calculating the slope of a straight line connecting two adjacent  $a$  versus  $t$  data points. The calculated average crack growth rate is assigned at a point midway between each pair of data points. To avoid the time-consuming process of data reduction, a computer program was written to calculate  $K_I$  and  $da/dt$ .

## Results and Discussion

When cracks occur, whether resulting from the manufacturing process or from service loads, the stresses near the crack tip will be redistributed. Depending on the magnitude of the local stresses and the local strength, various defects, microvoids or microcracks, can develop in the crack tip region. And, depending on the severity of these defects, crack growth behavior can be significantly affected.

Experimental results indicate that crack tip blunting takes place both before and after crack growth. The material at the tip of the crack suffers very large elongation and is nearly straight. The highly strained or damage zone extends ahead of the crack tip, appearing as an equilateral triangle with the crack tip as its base. This damage zone is known as the failure process zone, which is a key parameter in viscoelastic fracture mechanics. When the local strain reaches a critical value, small voids are generated in the failure process zone. Due to the random nature of the microstructure, the first void is not restricted to the surface where the maximum normal strain occurs. Since the tendency of the filler particle to separate from the binder under a triaxial loading condition is high, it is expected that voids, or a damage zone, will also be generated in the specimen's interior. Consequently, there are a large number of strands, essentially made of binder material, which separate the voids that form inside the failure process zone. As the applied strain increases with time, material fracture occurs at the blunted end of the crack tip. This will always be the location of the maximum local strain. The failure of the material between the void and the crack tip causes the crack to grow into the failure process zone. This kind of crack growth mechanism continues until the main crack tip reaches the front of the failure process zone. When this occurs, the crack tip resharps temporarily.

The damage and crack growth mechanisms discussed in the above paragraphs are the basic mechanisms observed in this material under both ambient and high confining pressures. The effect of pressure is to suppress the damage and evolution processes.

A typical plot of stress-strain curves at a constant strain rate of 16.67 in/in/min under ambient and 1000 psi confining pressures are shown in Fig. 2. From Fig. 2, it is seen that the maximum load increases significantly when the pressure is increased from ambient to 1000 psi. However, the magnitude of the confining pressure has no significant effect on Young's modulus. Theoretically, the magnitude of the confining pressure should have no effect on the Young's modulus due to the incompressibility of the material. The slight variation of the Young's modulus is due to the scatter of the test data, material variability, and the reason that the material is not truly incompressible. It is interesting to point out that under the high confining pressure condition, the critical strain,  $\epsilon_c$ , for the transition of the linear response to the non-linear response of the material is increased. Since the material's response is closely related to the damage state in the material, the change of the

aforementioned parameters is believed due to the suppression, or the delay, of the development of damage under the higher confining pressure condition.

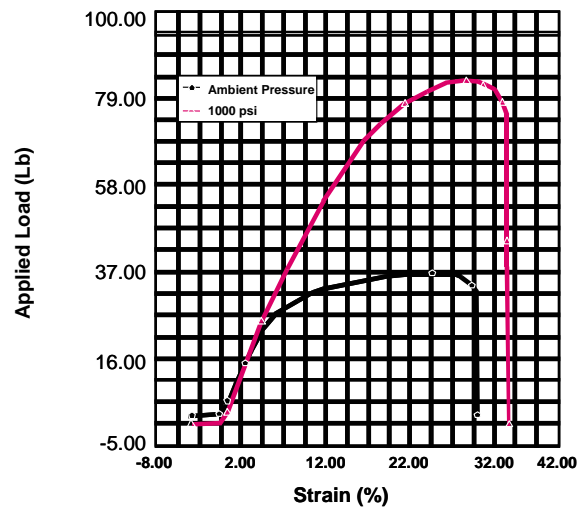


Fig.2 Uniaxial Stress-Strain Curves.

A plot of crack length versus time is shown in Fig. 3. In Fig. 3, the maximum applied load is also marked on the crack growth curve. It is interesting to point out that under the confining pressure condition, the crack grows stably not only beyond the maximum applied stress but also near the fracture of the specimen. This phenomena is significant different from the crack growth behavior of the same material under ambient pressure. Under ambient pressure, crack growth becomes unstable when the applied load exceeds the maximum applied load.

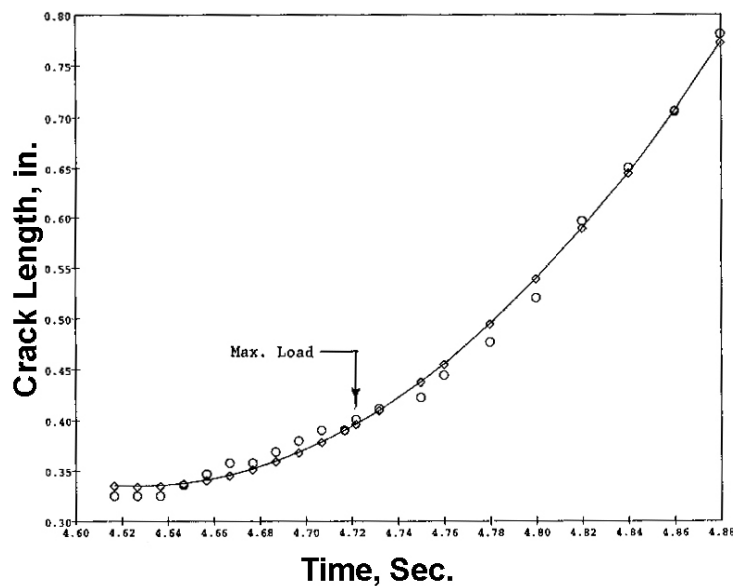


Fig. 3 Crack Length versus Time Curve.

The determination of the crack growth rate requires an analysis of discrete data relating the instantaneous time,  $t$ , to the corresponding crack length,  $a$ . Due to the nonhomogeneous nature of the highly filled elastomer the measured data shows a considerable scatter. Therefore, it is anticipated that a smooth and steadily increasing relationship between the crack growth

rate and time is difficult to obtain, and the different methods of  $da/dt$  calculation may result in different solutions. From the results of the crack growth rate calculation, the secant method introduces a pronounced fluctuation of  $da/dt$ . In other words, the crack growth process consists of a slow-fast-slow phenomenon. As mentioned earlier, the damage process is a time-dependent process, and it required some time to develop a failure process zone at the crack tip. Thus, the crack growth process consists of blunt-growth-blunt and slow-fast-slow phenomena, which is highly nonlinear. The fluctuation of  $da/dt$  is consistent with experimental observation. Based on experimental evidence, in general, the crack does not grow in a continuous and smooth manner. During the crack growth process, crack growth rate both accelerates and decelerates. Therefore, the secant method appears to provide the best estimate of both the actual crack growth process and the actual crack growth rate.

Plots of  $da/dt$  versus  $K_I$  for different initial crack lengths and confining pressures are shown in Figs 4 and 5. For a given confining pressure, the crack growth curve of the short crack is above that of the long crack. In other words, for a given Mode I stress intensity factor the short crack grows faster than the long crack. It is interesting to point out that the differences between the short and the long crack growth data are small especially under the low confining pressure. Therefore, on the first approximation, we assume that the crack growth behavior is independent of the initial crack length. Under this condition, for a given confining pressure, the short and the long crack growth data were combined, and regression analyses were conducted to determine the regression lines and the relationship between  $da/dt$  and  $K_I$ . The results of the regression analysis, shown as the regression lines and the crack growth models with the correlation coefficients,  $R$ , are included in Fig.5. The same set of data were replotted to show the effect of confining pressure on the crack growth behavior (Fig.6). According to Fig. 6, for a given  $K_I$ ,  $da/dt$  decreases as the confining pressure is increased.

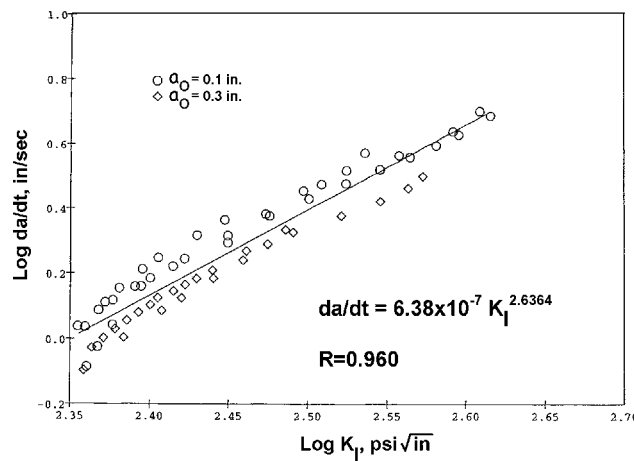


Fig.4 Crack Growth Rate versus Mode I Stress Intensity Factor (Pressure=500psi).

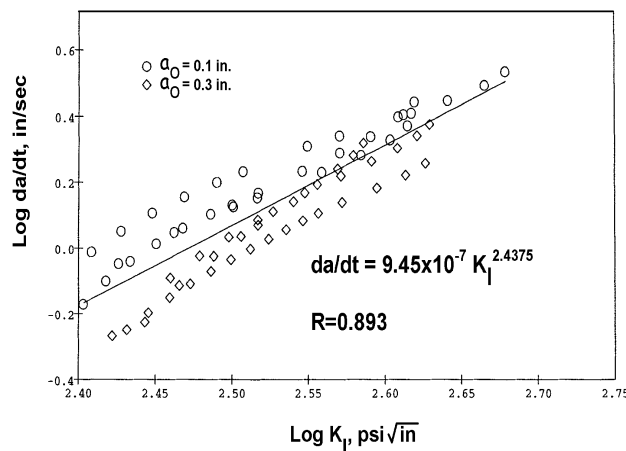


Fig. 5 Crack growth rate versus Mode I Stress Intensity Factor (Pressure=1000psi).

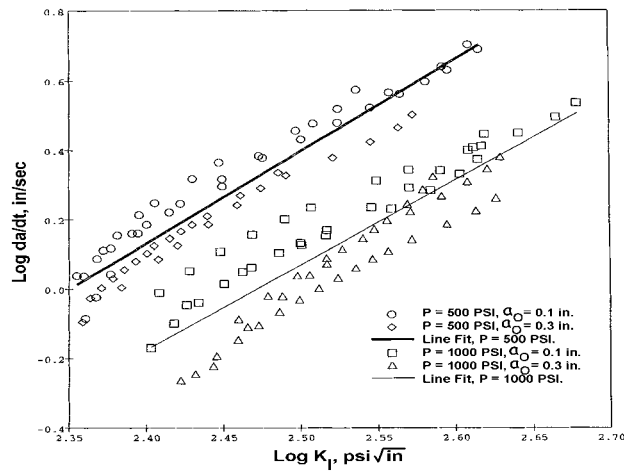


Fig. 6 Crack Growth Rate versus Mode I Stress Intensity Factor.

## Conclusions

In this study, the effects of confining pressure and the initial crack length on the crack growth behavior were investigated. Experimental findings reveal that under confining pressure, cracks grow stably near the fracture of the specimen. They also reveal that, for a given Mode I stress intensity factor and a given confining pressure, the short crack grows faster than the long crack. In addition, for a given Mode I stress intensity, the crack growth rate decreases as the confining pressure is increased, and a power law relationship exists between the crack growth rate and the Mode I stress intensity factor.

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